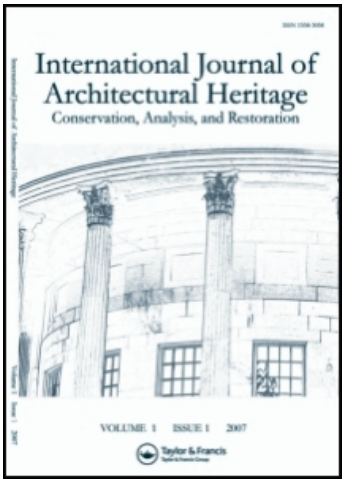

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Optical Documentation Techniques for Condition Assessment of Facades: A Tentative Evaluation of Three Case Studies Executed in Göteborg and Vienna

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OPTICAL DOCUMENTATION TECHNIQUES FOR CONDITION ASSESSMENT OF FACADES: A TENTATIVE EVALUATION OF THREE CASE STUDIES EXECUTED IN GÖTEBORG AND VIENNA

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A growing need for relevant information for long-term planning is a vital issue for the actors involved in management and maintenance of built heritage, as well as of built environments at large. Through its subsidiary companies, the publicly owned real estate and housing corporation Förvaltnings AB Framtiden, Inc., in Göteborg, Sweden, is administering 70,000 apartments. In Vienna, the Wiener Wohnen is an Austrian municipal housing corporation, administering 220,000 apartments. The dimensions of such building stocks indicate the relevance of user-friendly yet stringent methods for acquisition of valid information about types of construction, materials, and related issues of deterioration. A combination of existing and new methods for documentation and condition assessment of building facades, primarily based on optical techniques, has been designed and tested in accordance to the needed information indicated. This article reports on the outcome of three case studies comparing three methods for developing digital image, textured three-dimensional-models of existing buildings.

KEY WORDS: long-term maintenance, built environments, built heritage, facades, documentation, optical techniques

1. RESEARCH AIM AND BACKGROUND

1.1. Aim

The general intent of this article is to support strategies enhancing sustainable conservation and long-term maintenance within built heritage management and public housing management. A need for suitable and user-friendly methods of optical documentation supporting condition assessment of facades has been identified. Three generic multi-apartment buildings from the 1950s through the 1970s are reported in this the case study.

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The research reported here focuses on the development and elaboration of relevant means to create image-textured digital three-dimensional (3D) models of buildings. Vital parameters are image resolution, accuracy of 3D models, and time efficiency during data acquisition and during data processing. Integration of resulting image documentation into a geographic information system (GIS) map database is desirable since geographic relations between object, place, and ambience then can be established. A GIS application also enables storage of relevant text documentation such as reports of various inventory, damage assessment, and material analyses.

In the remainder of this section the stakeholders' (i.e., housing companies) point of view will be discussed and the existing means for creating textured 3D building models will be reviewed, providing an embedding for the research questions. In the following section, the case studies will be presented, comprising a description of the buildings, the documentation method, and the reported experiences. In the final section, conclusions will be drawn on the suitability of the investigated methods.

1.2. Background

1.2.1. Stakeholders' perspectives and needs Management, development, and technical maintenance of publicly owned multi-apartment buildings from the period indicated, encompass long-term strategic goals and short-term pragmatic goals as pair of complementing concepts. General long-term goals include, for example, upkeep of attractiveness of housing areas, identification of viable strategies for sustainable energy solutions, and enhancement of knowledge about current building materials and related issues of building pathology. Short-term goals might be related to sudden and unanticipated technical problems, which call for immediate attention, or anticipated needs of recurrent technical maintenance.

The selection of a specific measure addressing problems of building pathology is based on evaluation of various sets of information. This information is usually derived from observations made by in-house staff, from damage assessment made by external consultants, and from observations made by residents (P. Pirosanto, Property Manager, Bostads AB Gårdsten, Inc., personal communication, June 2008). Each housing company has developed the current systems for acquisition, storage, and analysis of information. On the corporate level a process has recently been initiated with the aim to establish a comprehensive software system for operation and maintenance planning, planned to be used by the subsidiary housing companies in Göteborg (J. Niklasson, Director of Technical Maintenance, Bostads AB Poseidon, Inc., personal communication, October, 2008).

In connection with previous research (Meiling, 2009), a lack of a theory-driven and application-oriented configuration of established and innovative relevant instrument technologies has been identified, which is an important starting point for this discussion. It is anticipated that accurate and user-friendly methods for documentation before, during, and after any direct intervention, and in connection to condition assessment, will facilitate identification of relevant information and thus the process of decision-making prior to the selection of a relevant treatment. The paramount reason in heritage recording is the identification and documentation of vital characteristics, constituting the point of departure for valorization and guiding the conservation or restoration process. It might be argued that documentation of vital architectural and ambient characteristics identified in what may be defined as generic built environments by means of optical techniques, constitute an underused methodological potential in processes of upkeep and development of attractiveness of

a housing area. Documentation based on optical techniques is likely to provide an added value to management and planning of maintenance and development of built structures and their ambience. A geometric (i.e., 3D) model, textured with photographic images, of any building is a vital source of image data and image information, preferably embedded in a georeferenced context (i.e., in a GIS application). Such documentation can be analyzed and interpreted at different occasions and by different persons and compared with new observations.

1.2.2. Research context The needs for sustainable and integrated conservation, long-term maintenance, and documentation of built environments, including built heritage, constitutes a vital challenge, in terms of scientific scholarly research and stringent professional management (Rosvall, 2006). The basis for the work presented is the *Documentation and Maintenance Planning (DoMaP) model*, a model for documentation and analysis of facades of modern buildings (Meiling, 2009). Image-textured 3D building models are supporting documentation and maintenance in DoMaP, and thus efficient and user-friendly methods for their generation need to be identified and developed.

Digital close-range photogrammetry (CRP) and digital photography are evaluated as principal documentation methods in the DoMaP model. It is well known that CRP enables capturing of image data that is characterized by surface continuity and 3D geometry (Carbonnell, 1989), and that derived 3D data mediates relevant measurable information about the shape, size, texture, and position of the object (Kraus, 2007). Terrestrial laser scanning (TLS) provides topological surface data (point clouds); the result might be a virtual closed surface model that can be textured by high-resolution color images captured by means of CRP. TLS implies relatively automated procedures for data acquisition and results in huge amounts of data; CRP is less automated and with less resulting data. These two optical measurement techniques are often combined within the fields of architectural documentation, indoors as well as outdoors, and city modeling (Jansa et al., 2004). Digital photography is a user friendly and less expensive documentation technique compared with TLS and CRP and requires little post-processing of data. Thus digital photography often is used in situ for ambience documentation, object documentation. and detail documentation when 3D is not required.

Methods and techniques for advanced digital modeling and documentation of architectural heritage are developed and evaluated since several years (Dorninger and Briese, 2005; Dorninger, Kippes, and Jansa, 2005; Nothegger and Dorninger, 2007. At the University of Technology of Vienna, where one of the case studies was conducted, this research and technological development (RTD) is pursued in close collaboration with the management of Schönbrunn Palace in Vienna; in this case, data acquisition is based on TLS, combined with digital CRP. Modern laser scanners allow very high measurement rate (thousands of points per second). Data redundancy is used to reduce measurement errors, which in turn provides point clouds with high precision from which highly accurate geometric models can be determined (Nothegger and Dorninger, 2007). Despite relatively successful RTD in this field, the identified possibilities are not utilized in a broad sense among real-estate managers, partly due to the huge amount of data, which requires extra competence in handling of this data and resulting models.

Historic buildings are often profoundly complex in terms of 3D design and protruding details. Modern buildings are often characterized by a relatively simple external geometry, indicating the relevance of a simple documentation methodology satisfying the needs for overall documentation of large housing areas. Precision requirements in terms of

3D geometry can in many cases therefore be reduced to centimeters or decimeters, while demands on image quality in terms of high resolution and details can be increased. High-resolution images of facades can effectively display cracks, concavities, biogrowth, for example.

1.2.3. Methodological context When data capturing is performed by means of metric techniques, such as photogrammetry and laser scanning, it is possible to execute quantitative analyses of the data acquired. Analysis of non-metric information, derived from non-metric photography will result in qualitative interpretations. The quality of resulting documentation is dependent not only on a specific method and performance of technique applied but also on the specific light and weather conditions and the surface characteristics of the facade material, as well as the skill of the photographer.

The methods used for acquisition of geometry in this article are selected from a range of relevant documentation methods. By observing with total stations or making tape measurements, all relevant points of a building for generating the 3D model must be identified during acquisition on site. This necessity is a disadvantage because additional measurements, such as for a model of a facade detail, require another field trip. Especially photogrammetry does have the advantage that a permanent record of the scene is generated by data acquisition (i.e., taking an image). From the recorded images, the reconstruction of relevant building points is performed in the office, which is also possible many years after the initial acquisition. Photogrammetry can be performed by taking oblique images from the ground only or with images shot at right angle to the facade. The latter requires elevated positions for taking exposures. Laser scanning is similar to photogrammetry in the sense that a permanent record of the entire scene is generated. However, in contrast with gray or color images, laser scanning acquires a dense set of points. These points, expressed by their 3D coordinates, are spread over the entire building surface.

Finally, generalized building and roof geometry is often available in the form of digital maps, such as municipal base maps. Base map data can be acquired from overlapping aerial photographs, called *stereo pairs* (Kraus, 2007). Such base map data enables 3D viewing and 3D digitizing of roof shapes, correspondent shapes of the footprints of the buildings on the ground, and the distance in between constituting the building height. The base map also contains topographical 3D data of the ambient environment of the buildings. Thus, 3D models can be generated from the digitized roof shapes, footprints, and building heights in the base map.

2. EXPERIMENTAL SET-UP

2.1. Introduction

A tentative comparative evaluation of three ways of obtaining image-textured 3D-models of existing buildings was executed. The evaluation is based on three documentation projects performed in February 2007 in Göteborg, Sweden (case 1), October 2007 in Vienna(case 2), and March 2008 in Göteborg (case 3). Table 1 provides an overview of the methods used in each case. The buildings documented in Göteborg are owned and administered by one of the municipal housing companies within the Framtiden Group owned by the City of Göteborg. In the case of Vienna the building belong to the Wiener Wohnen owned by the City of Vienna.

Table 1. Cases and methods used

Methods Cases	Close-range photogrammetry (CRP)	Non-metric photography	Terrestrial laser scanning (TLS)	Three-dimensional data from base maps	Sky lift
Case 1	Yes	No	No	Yes	Yes
Case 2	No	Yes	Yes	No	No
Case 3	No	Yes	No	Yes	No

Figure 1. Photographs of (a) 9-story slab-block in Göteborg, by architect John Snis; (b) 4-story lamellar building in Vienna, by architect Otto Niedermoser; and (c) three to five story lamella block in Göteborg, by the architectural firm White.

The three buildings are rather different in shape and size in comparison to each other, and their surrounding environment display variations as well. These factors, together with pros and cons of the equipment used, influence the workflow and accessibility during data acquisition. Thus, the results from the evaluation of methods and performances are tentative.

Digital CRP combined with 3D information derived from municipal base map data was used in case 1. The structure documented is a curved nine-story residential slab block with a pen roof, and displaying a horseshoe plan (Figure 1a). The length of the curved structure is approximately 500 meters, its height is 22 meters, and its width is 11 meters. The building was constructed in 1959. Asbestos-fiber reinforced cement sheets constitute the facade cladding. The facades do not display protruding elements. Balconies and windows are aligned with the flight of the facade, emphasizing the flat facade character. Situated on one of Goteborg's elevated points above sea level, it is exposed to heavy winds, rain, and air pollutants, primarily from south and westerly directions. Consequently the asbestos sheeting facing these directions is severely deteriorated (Figure 2). Considerable fluctuations over time in outdoor temperature contribute to the climatic stress on the facade material.

Digital photography and TLS were used in case 2. This object is a geometrically simple lamellar residential building constructed 1963–1964, with a brick wall structure and plastered facades (Figure 1b). The approximate length of the structure is 30 meters, its height is 10 meters, and its width is 11 meters. It is four stories high, has a pitched roof and a suspended pathway connecting the upper floors to the neighboring building. Three of its facades are perforated by a regular pattern of windows, while the connecting pathway is blended by a light curtain-wall construction. The facade surfaces seem to be in fairly good condition, despite displaying discoloration phenomena, small cracks, and loss of material in the superficial layer of the plaster (Figures 3a and 3b).

Figure 2. Photograph of deteriorated asbestos sheet and poor repair work.

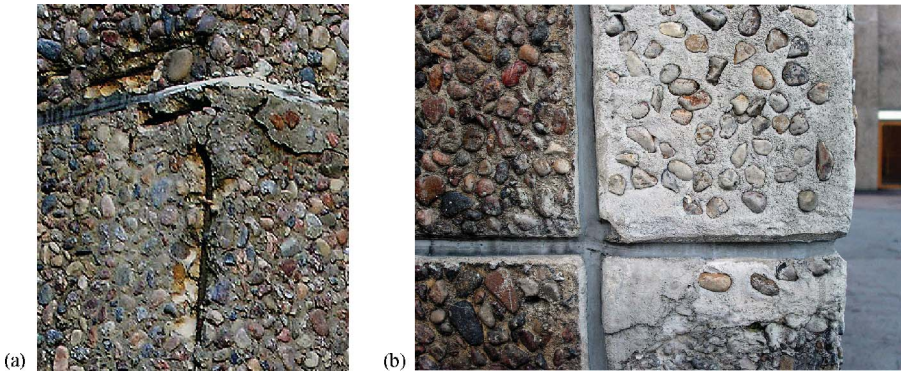

Figure 3. Photographs of (a) corrosion of steel bars and spalling of concrete, and (b) poor repair work.

Digital photography combined with 3D information derived from base map data was used in case 3. The object is a three-to-five story-high residential lamellar building constructed in the late 1960s, with prefabricated concrete facade elements with intentionally exposed aggregates, and a flat roof construction (Figure 1c). The approximate length of the structure is 300 meters, its height is 10 meters, and its width is 11 meters. The building is situated in a terrain characterized by bedrock formations and greenery. Balcony projections are distributed on the facade towards the inner courtyard, providing a dynamic visual effect contrasting to the flat facades towards the street. These facade elements suffer from severe carbonation-induced corrosion of the steel rods, and poorly executed repair works (Figure 4).

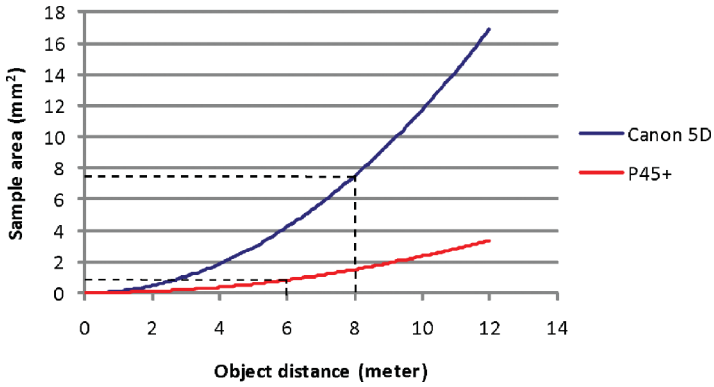

Figure 4. Graph of the sample areas per pixel at various distances for Canon EOS 5D/24 mm f/2.8 and P45+/45 mm f/2.8, respectively; the dotted lines indicate the range of sample area in relation to object distances.

2.2. Material

Image acquisition was performed with a digital single-lens reflex camera with a full-size sensor in case 1 and 2 (Canon EOS 5D [Canon, Tokyo, Japan]). The camera was calibrated by means of software processing of images captured of a 3D array of known measuring points, attached to a cubic steel frame that is fixed to a wall. The software used is GenTri–General Triangulation, which is a bundle adjustment system developed by the Swedish photogrammetrist Dr. Rune Larsson in connection with his dissertation (Larsson, 1983). Today this software is a component in various products provided by Photo Mess Systeme (PMS AG) in St. Margrethen, Switzerland.

In case 3 a medium format camera with a larger sensor was used (Phase One P45+). This camera was not calibrated. System specifications are indicated in Table 2. Figure 5 indicates object-sample areas per pixel at various distances to the object for both camera systems. A sample area of an object is correspondent through geometry to a pixel in the sensor. The distance to the object, the focal length of the lens, and its angle of view, and the sensor resolution defines the potential of the camera system to distinguish details of certain areas in objects. Other vital parameters are color depth (i.e., bit per channel), lens quality, and weather and light conditions during exposure, as well as surface characteristics of the photographed object. In connection it is important to consider that the angle of view of a

Table 2. Specification of camera systems used

Cameras Specifications	Canon EOS 5D	Phase One P45+
Resolution	12.7 million pixels	39 million pixels
Sensor	CMOS, 35.8 × 23.9 mm	CCD, 36.8 × 49.1 mm
Active pixels	4368 × 2912 pixels	7216 × 5412 pixels
Color depth	12 bits per channel	16 bits per channel
Lens	24 mm f/2.8	45 mm f/2.8
Angle of view	Horizontal: 74°; Vertical: 53°	Horizontal: 57°; Vertical: 45°
File storage	Raw (CR2); JPEG	Raw (IIQ)
Weight	With lens ∼1 kg	With lens ∼2.2 kg
Price (approximate)	€ 3 500	€ 35 000

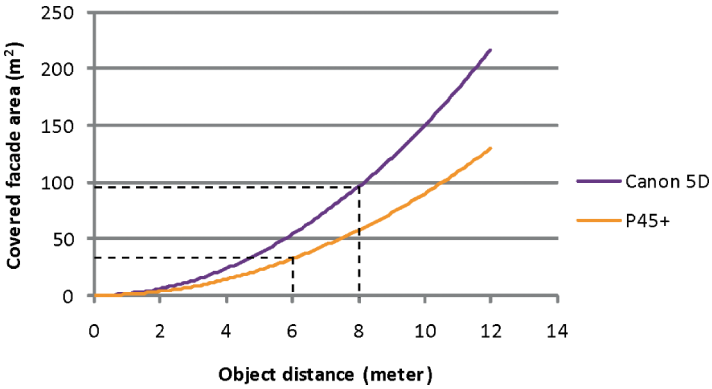

Figure 5. Graph of the coverage per exposure at various distances for Canon EOS 5D/24 mm f/2.8 and P45+/45 mm f/2.8, respectively; dotted lines indicate the range of covered facade area per exposure in relation to object distances.

lens is defined by its focal length and the size of the image sensor used. The theoretic values of calculated sample areas for the two camera systems used range from approximately 0.8 mm^2 (Phase One P45+) at an object distance of 6 meters to 7.5 mm^2 (Canon 5D) at 8 meters (Figure 6).

The image data captured is stored as raw image files, on the memory card of the cameras. The Canon camera can store JPEG copies as well. Raw image data is non-processed data and cannot be properly viewed without prior processing; raw-files are thus comparable with analogue film negatives. Raw image files can be converted into readable digital formats, such as JPEG (ISO10918-1) or TIFF (Adobe Systems, Inc., [San Jose, CA, USA], copyright holder to the TIFF specification). The Canon camera has been pre-set to capture images in a neutral mode. This setting means that no image enhancing adjustments have been made, in order to provide images containing true information based on the conditions on site. The Phase One camera does not allow for this type of pre-set. Compression by means of JPEG ISO-standard permits a color-depth of 8 bits per channel. Image processing into a TIFF-format allows utilization of the full color-depth of the image sensor, which are 12 bits per channel for the Canon EOS 5D and 16 bits per channel in the case of Phase One P45+. The resulting image data after image processing were stored as TIFF-files.

A Riegl TLS was used for measurement and data acquisition in case 2 (Table 3). The scanner was mounted on a tripod and connected to a laptop for data storage. In the cases 1 and 3, 3D data were obtained from the municipal base map of Göteborg, which

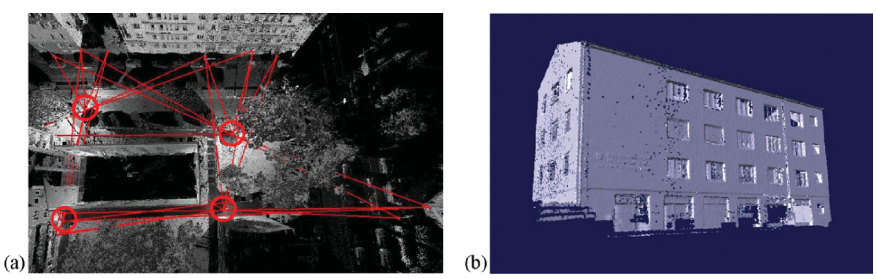

Figure 6. Images of the scanned building: (a) point-cloud with four major scan positions and lines of sight to corresponding reflecting targets, and (b) surface model.

Table 3. Specification of scanner system used

Scanner Specification	Riegl LMS Z 420i
Measurement range	0–800 m (measurement noise below 50 m ranges as specified)
Accuracy	+/− 10 mm (standard deviation)
Measurement rate	Up to 11.000 points/sec
Scanning range	360° horizontal; 80° vertical
Weight	16 kg
Operating system	Software "RiscanPro"
Price (approximate)	€ 150 000

derives from aerial photographs of the built environment of Göteborg. These aerial images are captured by expert enterprises on commission by the City Surveying Office at the City Planning Office of Göteborg. Through an agreement between the City Surveying Office and Chalmers University of Technology all municipal base map-data is accessible on a campus-server for research-purposes. These data is updated every 6 months. The 3D data is retrievable, such as in the digital formats "shape" and "drawing", or in acronyms "SHP" and "DWG", respectively, which are common formats for storage of two dimensional and 3D data. The shape format is developed by Environmental Systems Research Institute, Inc. (ESRI) (Redlands, CA, USA), and is a commonly used format in geographic information systems software. The dwg format is developed by several actors, primarily by Autodesk, Inc. (San Rafael, CA, USA), which is the license-holder of the format. The dwg-format is a commonly used format in CAD-applications. The base map was also used as a carrier of documentation and information during the design of the GIS application in case 1.

2.3. Methods

Keeping in mind the considerable size of housing areas involved, selected techniques for photographic documentation and acquisition of 3D data shall preferably enable operating flexibility, and relevant measurement accuracy, at reasonable costs. The main function of the resulting 3D models is to serve as rough wire models for image texturing, with focus on the principal geometry of the building.

The cameras were mounted on a tripod during image acquisition. During on-site work in Case 1 the camera was operated from ground level, and from a sky-lift. The images were captured orthogonally to the facade surfaces and along a base line in parallel to the facade. The distance to the facade surface during capturing was ranging from 6 to 8 meters. The images were captured with a 60% overlap, thus obtaining the stereo pairs needed for later processing of orthophotos of the facades. Further, at each position the viewing directions were in parallel to each other, and as indicated in right angle to the base line and the facade surface. By following this procedure the requirements of what is described as the "normal case" were fulfilled in accordance to standardized photogrammetric procedure. For user friendly yet stringent introductions to principles and procedures of photogrammetry I draw upon web-tutorials available at the International Society for Photogrammetry and Remote Sensing (ISPRS, 2009).

In cases 2 and 3 image acquisition was operated from ground level, and without overlap since 3D-model generation by CRP was not a requirement. Operating distance from the

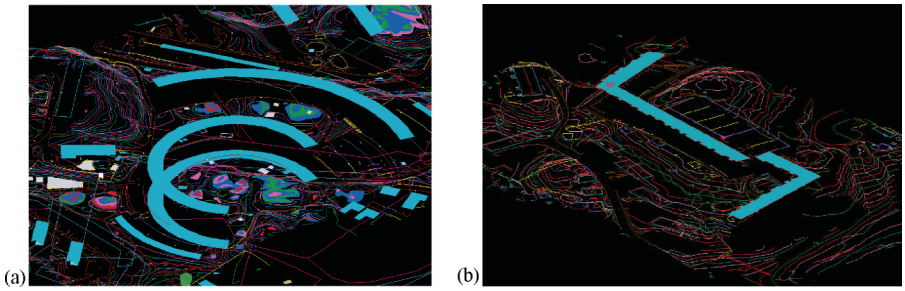

Figure 7. Print-screen images of roof shapes: (a) case 1, and (b) case 3 (data from the City Surveying Office of Göteborg, Sweden).

facades varied from 6–8 meters, due to the size of the facades, and objects hindering an adequate exposure.

In case 2, the TLS positions were selected according to best visibility of relevant object details and maximum representation efficiency. Thus, scanning covered each of the four corners of the building, complementing each other in such a manner that scanning shadows created by facade recesses were eliminated. At two positions added scans became necessary in order to cover the entire object, resulting in a total number of six scan positions (Figure 7a). The two added scans were due to the 80° vertical aperture of the scanner, which proved to be an insufficient angle of aperture at the operating distance of approximately 5 meters at these two positions. Thus, an extra tilt of the scanner was required in order to cover the upper part of the building.

Planning of a scanning-project is vital in order to acquire a time-effective workflow, including especially the identification of relevant scan positions. Furthermore, experience is required for optimal placement and distribution of reference targets, preferably made of a glossy reflecting material. These targets remain on fixed positions while the scanner is moved from one scan position to the next. With the fixed reference targets, all the points acquired and spread over different surfaces from different scan positions can be brought into the same coordinate system (i.e., the scans are oriented). This orientation enables a satisfactory measurement accuracy during scanning, thus resulting in an accurate 3D model of the scanned object. The reference targets are typically small (approximately 5 cm in diameter) circular stickers. If, in general, not less than four such targets at each scanning position are scanned, a satisfactory orientation of the scans can be achieved. Figure 7a indicates the four principal positions of the scanner and lines of sight to corresponding reflecting targets at each scanner-position. Entire 360° scans were performed and to facilitate and speed up the scan orientation the targets were distributed in the surrounding built environment. For the orientation of the scans, two different software registration methods have been tested. The first method uses the reflecting targets as tie-points. The alternative method does not require targets in one regard, but in another regard requires more complex algorithms, especially the ICP algorithm (Iterative Closest Points [Besl and McCay, 1992]), implemented in software packages. The first orientation method can easily be carried out in situ and results in a ring orientation, one scan to the next with four reference targets visible in each new scan. The second orientation method was performed after having concluded data acquisition, by means of a separately licensed software algorithm tool from Riegl LMS (Horn, Austria).

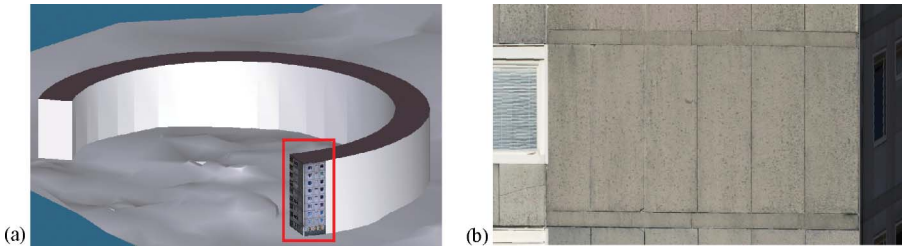

Figure 8. Images of case 1: (a) three-dimensional (3D) model, with the frame indicating the image textured part, and (b) detail of the orthophoto from the 3D model.

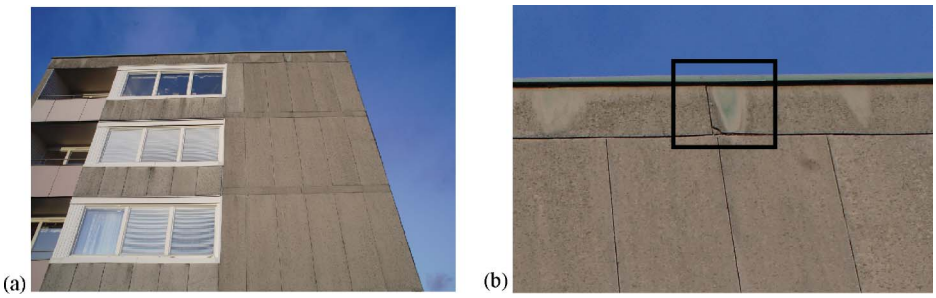

Figure 9. Photographs of (a) case 1, tiff-image of the three upper stories of the southwest facade with asbestos cement sheeting, and (b) detail with black frame indicating surface soiling and discoloration.

The 3D models in cases 1 and 3 were generated from 3D information deriving from the municipal base map and aerial stereo-pairs, which allowed digitizing the roof shapes (Figure 8) and generation of 3D building models (Figure 9). The metric accuracy of 3D data used to generate the 3D building models is within the range of decimeters. In Case 1 image data were processed into orthophotos of the facades by means of a software program from ESPA Systems, Ltd, in Espo, Finland. The manual process includes measuring of known points and distances in the stereo model, and generation of a topographic "height model" of the facade. The software program automatically generated the orthophotos. Finally these orthophotos were referenced manually to the 3D building model (Figure 9). Prior to manual image referencing in Case 3, the images were stretched in order to fit to the generated 3D building model. This stretching means that every pixel in images used was slightly skewed and distorted in a metric sense.

2.4. Experimental Data

Digital binary image data are stored as raw image files on the camera memory card, with a capacity of 12 bits color-depth or 16 bits color-depth for Canon and Phase One respectively (Table 2). The raw image files constitute the primary experimental data. Image processing of raw files into TIFF files resulted in viewable images (Figures 10 and 3). Processed images (i.e. compressed and slightly adjusted sharpness and color), constitute the secondary experimental data. Adjustments were executed without the use of standard color reference panels, which has been identified as a drawback. The software used for image processing is Adobe Photoshop CS (Adobe Systems Inc., San, Jose, CA, USA). The

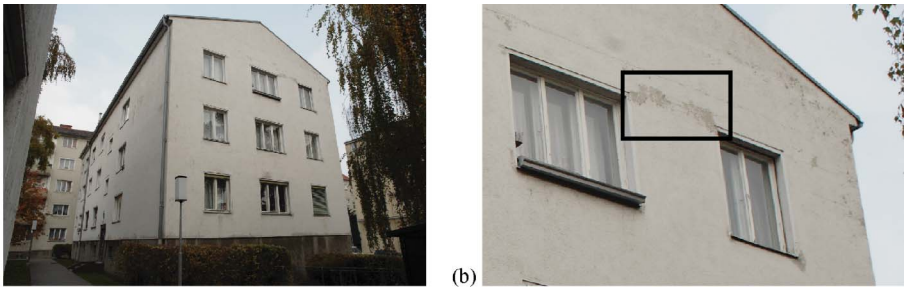

Figure 10. Photographs of case 2 southwest facade: (a) plastered brick wall, and (b) detail with frame indicating loss of superficial facade material.

higher degree of detail in images captured by the Phase One camera is due to higher optical qualities of the lens system, its larger image sensor, as well as a richer color depth (Table 2). However, images that have been captured with the Canon camera also display discernable surface-phenomena and damages with satisfactory resolution. Such surface phenomena are soiling and discoloration, for example (Figure 10).

Topological surface data (object surface points) measured in three dimensions (x, y, and z) captured during on-site work in case 2 by TLS were digitally stored on a laptop. The point clouds constitute the primary experimental 3D data (Figure 7a). The next mode of experimental 3D data is the surface model, which is based on topological boundary representation where the continuous surface between these boundaries has been modeled by triangulation derived from original points (Figure 7b).

2.5. Results

2.5.1. Acquisition of image data The number of exposures needed for image acquisition and amount of time consumed for work on site varied in the three documentation projects primarily due to the size of facade areas, use or no-use of sky lift, and depending on the camera system used (Table 4). Other important factors influencing the workflow are characteristics of the surrounding environment, such as the topography and objects obstructing the view of the camera. Reduced accessibility required that images were captured at a closer distance to the facade, resulting in increased perspective distortion and overlapping of images, and thus increasing number of exposures needed to cover the facade surface.

Case 1 required most efforts on-site (Table 4). This finding was anticipated because the aim was to establish a 3D model textured with orthophotographs, which is more time-consuming considering time needed for data-acquisition. In cases 2 and 3 image capturing

Table 4. Cases and methods used with regard to time consumed and facade area covered by each method

Parameters Projects	Optical device	Sky lift	Facade (m^2)	Exposures	Scans	Time on site (hrs)	m^2/exp	m^2/hr	Time in office
Case 1	Canon	Yes	540	44	—	4	12	135	40
Case 2	Canon	No	860	42	—	2	20	430	—
	Riegl	No	860	—	6	2.5/ 1	—	344/860	—
Case 3	P45+	No	460	18	—	0,75	25	613	10

was less time consuming because orthophotographs were not needed, and cameras were easier operated from ground. However, limited accessibility to the facade facing the inner yard during image acquisition in case 2 resulted in increased number of exposures in comparison to the facade facing the street. Image acquisition in case 3 was completed with very little obstructive influence from the surroundings. To summarize the results in terms of time consumed on-site in relation to covered facade area, the performance of the Canon system resulted in 135 m^2/hour in case 1, compared with 430 m^2/hour in case 2 when only non-metric images were required. The performance of the P45+-system resulted in 613 m^2/hour, also when non-metric images were required (Table 4).

It shall be stressed that image capturing from ground level implies increasing occlusion of image data in the higher parts of tall buildings. In case 3, the very high resolution capacity of the images captured by the P45+ camera could not be utilized in the 3D model because the specific 3D software used could not handle the total amount of these relatively large images, in terms of amount of bytes. Thus, when a close visual study of high-resolution TIFF images with unaltered shape of the pixels is needed it can be done with a standard image-viewer (Figure 11). The original unchanged RAW files are stored on a PC for future image processing and interpretation.

2.5.2. Acquisition of surface data As previously indicated the scanning of the facades during case 2 required six single scans recorded from four major scan positions (Figure 7a). The planning and execution of distributing the 15 reflecting targets consumed a period of 30 minutes, while the total time of operating the registration was higher, due to needed human interaction. In each single scan position, all the automatically extracted signals had to be controlled, and false reflecting targets manually deleted while those not retrieved had to be added. Furthermore, all targets were scanned adopting the finest scanning resolution of 0.002° step-width in order to maximize accuracy of the results. This scanning requirement added an extra 10 minutes for each scan position. Calculating 30 minutes for preparation of targets, and six scan positions multiplied by 10 minutes for fine scans of the targets, the total orientation time needed on-site adds up to 90 minutes. The scans for surface data acquisition took 4.5 minutes each. Together with the time required for moving from one scan position to the next, the total on-site time is approximately 2.5 hours. Based on the fine scanned reflecting targets, the second scan was oriented to

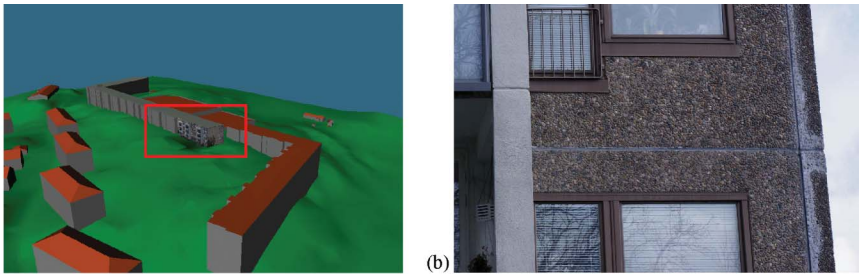

Figure 11. Case 3: (a) three-dimensional (3D) model, with rectangular frame indicating the part textured with stretched images, and (b) detail showing a non-altered high-resolution tiff-image displayed with a standard image viewer.

the first one, the third scan to the two first ones, etc. The registration error of this standard procedure is 10.6 mm considering all six scans. This error describes the average discrepancy encountered at the tie points, i.e. the targets.

Alternative to the sequential approach, a multi-station adjustment (MSA) was applied, in which the orientation of all scans is determined simultaneously. This MSA is provided by the scanner software and does not require fine scanned targets. It can be seen as an implementation variant of the ICP algorithm. This resulted in a registration error of 5.6 mm, which is similar to the error of the sequential orientation. The MSA approach reduces the time on site because no targets are necessary by 90 minutes, but adds extra office hours for performing the MSA, in this case 50 minutes. This reduction of time needed on site results in a considerable increase of area-unit covered per time-unit, from 343 m2/hr to 858 m2/hr (Table 4).

2.5.3. Three-dimensional modeling and geographical information system

Through the process of digital image acquisition, acquisition of geometric data from base map data, and subsequent image texturing, 3D models of the documented buildings in cases 1 and 3 were developed (Figures 9 and 11). The 3D model developed within case 1, was integrated into a GIS application. The information is activated by hyperlinks connected to certain objects and positions in the base map of the GIS application. When activating such a hyperlink, the related information is opened in a separate window for viewing and reading. Such information connected to a building includes oblique aerial photographs, terrestrial

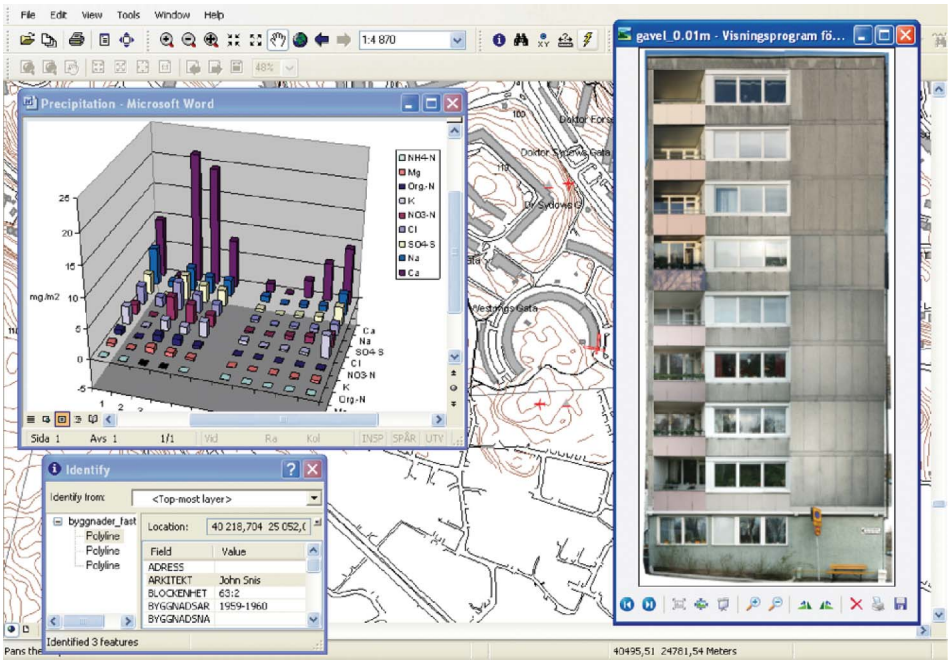

Figure 12. Case 1: The geographic information system (GIS)-based Documentation and Maintenance Planning (DoMaP) system enabling storage and display of image-textured three-dimensional (3D) models of buildings, facade photographs and orthophotographs, reports, and cadastral information.

facade images and facade orthophotographs, as well as written reports from various analyses (Figure 12). In case 1, the time required for processing orthophotos from the stereo pairs, 3D modeling of base map data, image texturing, design of a GIS application, and integration of resulting documentation runs up to approximately 40 hours. In case 3 the time required for 3D modeling of base map data and subsequent image texturing summed up to approximately 10 hours (Table 4). Two consultancy companies were assigned to execute this part of the process, Ramböll Sweden AB, Inc. (Göteborg, Sweden) in case 1, and Met Geo Info GmbH, Inc. (Vienna, Austria) in case 3.

3. CONCLUSIONS

Time consumption during image acquisition on site was considerably reduced when images were captured from ground instead of from a sky lift. It was difficult to keep the platform of the sky lift in stable position at an object distance of approximately 6–8 meters, defined as the appropriate range during image-acquisition in case 1. The difficulty to maintain a fairly fixed position became significantly problematic at an elevation of 10 meters and above. The advantage of using a sky lift as a standard procedure is to be questioned. However, it might be relevant to use a sky-lift when true orthophotos without occlusions and with homogeneous and high texture resolution are required.

It has to be stressed that documentation of a tall building such as the building in Case 1, from ground level, will provide relatively poor resolution in the upper stories, however with discernible surface-phenomena. Imagery captured with a viewing direction at perpendicular angle to the facade minimizes occlusions and provides consistent, i.e. one specific resolution, for the entire facade. As previously indicated this method requires the use of a sky lift. It is easier to capture images from ground level but it will lead to decreasing resolution for upper facade parts as well as occlusions in case of protruding elements. High-end cameras may alleviate the problem of decreasing resolution by taking exposures with higher-than-necessary resolution at ground level and still with satisfactory resolution at the eaves of the building.

Utilization of a medium-format camera, such as the P45+ used, facilitated image acquisition and workflow on site in comparison with the small format camera used here (i.e., Canon). Perspective distortion is less pronounced in the images captured with the Phase One system, in comparison to the Canon system, which contributed to less overlap during image acquisition, and thus increased coverage in terms of facade surface per exposure. Reduced perspective distortion and overlap during capturing with the Phase One system was also due to fewer objects obstructing the view, thus enabling capture at a more favorable distance to the facades. It is stressed that the obtained values in Table 4 provide a tentative evaluation of the performance in each case. The medium-format camera provided very detailed facade images, partly due to its larger sensor and greater color depth. The Canon camera is easier to operate on-site, compared with the larger and heavier P45+-camera, and provided relatively detailed facade-images. In order to reduce manual handling on site standard color reference panels were not used during image acquisition. However, considering the need for comparative evaluation of color changes in facade materials over time the use of standard color reference panels is to be recommended.

When orthophotos are needed, a more rigorous and precise methodology has to be adopted, possibly including utilization of a sky lift, in order to provide all image data

required, which logically implies a larger time-frame on site. Thus, selection of equipment and method has to be balanced to defined requirements, budget, and aim of each documentation project. It is to be noted that a visual study of photographs allows only a qualitative analysis and interpretation, and does not enable metric evaluation. Further, application of orthophotos requires geometric models, i.e. 3D models.

Acquisition of 3D data by means of TLS provides highly accurate and large quantities of data. Time consumption, due to manual handling of relatively heavyweight equipment during transportation from one scanning position to another, however constitutes a bottleneck. The entire instrumentation set-up required can be mounted either as an integrated mobile unit, or an autonomous scanning-vehicle. Such a solution might lead to a more effective workflow for scanning projects in urban settings. Successful planning of reflector distribution might be difficult due to obstruction of the scanners line of sight, by static and dynamic objects such as trees, buildings, vehicles, and pedestrians. A comparison between the two orientation methods presented in this article, shows that the orientation error for both methods reached quite similar values, at the level between 5 and 6 mm. Further, referring to time consumed in situ the method of sequential orientation using fine-scanned targets as tie-points required a total time for orientation and acquisition of surface data of approximately 2.5 hours, while applying simultaneous orientation by MSA merely required 1 hour on site. Utilization of algorithm software such as MSA analysis contributes to increased efficiency during scanning since larger facade areas are measured per time-unit.

The results presented in Table 4 indicate that the approach selected in case 3 has clear advantages in comparison with the approach in case 1 and 2. This finding seems relevant and important considering the identified need for user-friendly methods for overall documentation of relatively large housing areas. Simple, and user-friendly methods with lightweight equipment, facilitate the workflow and reduce time consumption and thus the cost for on-site work. Photography from ground proved to be the technique requiring least planning, as well as least amount of work-hours on site, yet with satisfactory result in terms of image resolution in the overall documentation, and with regard to needed generic applicability of the technique used. As indicated, this process concerns the work on-site and does not include 3D modeling.

The design of the GIS-application, generation of orthophotos and a 3D model of the building, and integration of the acquired data, required a relatively large time frame in case 1. However, when such a design once is established it is to be anticipated that it will be utilized with a long-term perspective. Generation of 3D models of buildings based on geometric base map data and subsequent texturing with detailed high-resolution 2D images seems to be a favorable means to establish sufficiently accurate documentation of built environments.

The use of GIS-based system with photographic records, including virtual image-textured 3D model of any building, is likely to support establishment of planning strategies for long-term maintenance and sustainable conservation operations. In the context of this discussion, the actual end-users of the established documentation are public housing companies. However, relevant end-users also comprise real-estate managers in general, city planners, various involved vocational operators and professionals, as well as tenants .Further, a firm need of joint venture-based RTD-cooperation is clearly observed, preparing for increased interaction between academic research, management professionals, and decision-making bodies, regarding documentation-projects in relation to management of

architectural heritage, and certainly also for the massive majority of generic buildings of different kinds.

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